

Constraining the star formation rate in the Solar neighbourhood with star clusters

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ABSTRACT

This paper investigates the star formation rate (SFR) in the Solar neighbourhood. First, we build the local age distribution function (ADF) with an updated sample of 442 star clusters located at less than 1 kpc from the Sun. Next, we define the SFR, compute the individual mass evolution of a population of artificial clusters covering the broad range of parameters observed in actual clusters, and assume $100 M_{\odot}$ as the low-mass limit for effective cluster observation. This leads to a simulated ADF, which is compared to the low-noise Solar neighbourhood ADF. The best match corresponds to a non-constant SFR presenting two conspicuous excesses for ages ≤ 9 Myr and between 220 – 600 Myr (the local starburst). The average formation rate is $\overline{SFR} \approx (2500 \pm 500) M_{\odot} \text{ Myr}^{-1}$, corresponding to the average surface formation rate $\overline{\Sigma_{SFR}} \approx (790 \pm 160) M_{\odot} \text{ Myr}^{-1} \text{ kpc}^{-2}$. These values are consistent with the formation rate inferred from embedded clusters (ECs), but much lower ($\lesssim 16\%$) than that implied by field stars. Both the local starburst and the recent star formation period require $SFR \sim 2 \times \overline{SFR}$ to be described. The simulations show that $91.2 \pm 2.7\%$ of the clusters created in the Solar neighbourhood do not survive the first 10 Myr, which is consistent with the rate of EC dissolution.

Key words: (*Galaxy:*) open clusters and associations: general

1 INTRODUCTION

It is currently accepted that star formation is scale-free and hierarchical, with high-velocity turbulent gas forming large-scale structures, while low-velocity compression forms small clumps (Elmegreen 2008). A natural consequence of this scenario is that young stellar groupings would be hierarchically clustered, with the great star complexes at the largest scales and the OB associations and subgroups, clusters and cluster sub-clumps, at the smallest (e.g. Efremov 1995). The bottom line is that star formation appears to occur primarily in clusters. Consequently, star clusters appear to be excellent tracers of the star formation rate (SFR) and history of the Galaxy, provided that their fundamental parameters - especially the age - are known.

However, star clusters have limited lifetimes. At the earliest phases, most of the embedded star clusters (ECs) dissolve into the field on a time-scale of a few 10^7 Myr. Dissolution here occurs mainly because the gravitational potential can be rapidly reduced by the impulsive gas removal by supernovae and massive star winds associated with this early period. Thus, a significant fraction of the stars, especially of low mass, end up moving faster than the scaled-

down escape velocity, and may escape to the field (e.g. Goodwin & Bastian 2006).

Dissolution also affects the open clusters (OCs) that survive the early phase. Even around the Solar circle, most OCs dissolve long before reaching an age of ~ 1 Gyr (e.g. Bonatto et al. 2006). The disruption timescale, in general, scales with mass as $t_{dis} \sim M^{0.62}$ (e.g. Lamers & Gieles 2006), which means that Solar neighbourhood clusters with mass in the range $10^2 - 10^3 M_{\odot}$ dissolve on a timescale $75 \lesssim t_{dis}(\text{Myr}) \lesssim 300$. This occurs because OCs continually undergo mass segregation and evaporation, tidal interactions with Galactic substructures, shocks with giant molecular clouds (GMCs), as well as mass loss due to stellar evolution. By decreasing the total cluster mass - and the collective gravitational potential, these processes affect the internal dynamics and accelerate the cluster dynamical evolution. Eventually, the majority of the OCs dissolve in the Galactic stellar field.

Thus, the only way for recovering the SFR using the observed star cluster population is by taking the mass-loss processes affecting clusters of different masses and orbits into account. To this effect, semi-analytical descriptions of the main mass-loss processes have become available recently (e.g. Lamers, Baumgardt & Gieles (2010);

Khalisi, Amaro-Seoane & Spurzem 2007). In the present paper we employ these process to simulate the mass evolution of a population of artificial clusters. Properties of the local SFR are then derived by comparing the simulated age distribution function (ADF) with that built for clusters in the Solar neighbourhood.

This paper is organised as follows. In Sect. 2 we build the ADF for the Solar neighbourhood. In Sect. 3 we briefly discuss the cluster mass-loss process. In Sect. 4 we simulate the observed ADF and use it to constrain the local SFR. Concluding remarks are given in Sect. 5.

2 BUILDING THE OBSERVED CLUSTER ADF

The number of star clusters with accurate age and distance determinations has been steadily increasing over the last years. This is particularly true for the very young clusters, most of which so embedded in their parent gas and dust cloud that their stellar content is essentially inaccessible to optical photometry. However, the availability of uniform, wide-field, and rather deep near-infrared surveys (e.g. 2MASS¹, GLIMPSE², some covering essentially all the sky (2MASS), has led to the discovery - and allowed a robust parameter derivation - of many such embedded clusters (ECs - e.g. Dutra et al. 2003; Bica et al. 2003; Kumar, Kamath & Davis 2004; Kumar, Keto & Clerkin 2006); Bonatto, Santos Jr. & Bica 2006; Ortolani et al. 2008; Bonatto & Bica 2009b; Bonatto & Bica 2009c; Bonatto & Bica 2010a), together with some old and/or very reddened OCs (e.g. Froebrich, Scholz & Raftery 2007; Bonatto & Bica 2007; Bonatto & Bica 2008; Bonatto & Bica 2009a; Froebrich et al. 2010; Bonatto & Bica 2010b).

Together with the several hundred objects already indexed in the widely-used star cluster databases WEBDA³ and DAML02⁴, the recent discoveries (together with parameter derivation for poorly-studied and/or unstudied objects) are proving invaluable in constructing a more detailed picture of the cluster ADF, especially in the Solar neighbourhood and for very young clusters (Sect. 4).

We started by searching WEBDA and DAML02 for clusters with available age (t_A) and distance from the Sun (d_\odot). However, given the amount of new data routinely published, it usually takes a considerable time for both databases to incorporate the recently discovered clusters, or to update previous entries with newly derived parameters. Then, we complemented the sample by searching the recent literature for clusters that still are not listed in either database. Cluster designations and coordinates have been checked among all sources (WEBDA, DAML02, and literature) to avoid duplicity. When multiple values of age and/or distance occurred, we adopted those based on colour-magnitude diagrams (CMDs), or the more recent. The fi-

nal sample contains 1718 clusters (ECs and OCs) with age and distance, of which 442 are closer than 1 kpc from the Sun⁵. By far, most of the parameters have been taken from WEBDA and DAML02, which do not provide measurement uncertainties. Thus, based on our experience in working with clusters of different ages and distances, we adopted the following uniform error attribution: 10% for $d_\odot < 1$ kpc, 15% for $1 < d_\odot(\text{kpc}) < 5$, 20% for $5 < d_\odot(\text{kpc}) < 9$, and 25% for $d_\odot > 9$ kpc; 35% for $t_A < 20$ Myr, 30% for $20 < t_A(\text{Myr}) < 100$, 20% for $100 < t_A(\text{Myr}) < 2000$, and 50% for $t_A > 2000$ Myr.

Age uncertainties are explicitly incorporated into the ADF, which is defined as the fractional number of clusters *per* Myr, $ADF \equiv dN/dt_A$. Formally, if measurements of a given parameter χ are normally (i.e. Gaussian) distributed around the average $\bar{\chi}$ with a standard deviation σ , the probability of finding it at a specific value χ is given by $P(\chi) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{1}{2}(\frac{\chi-\bar{\chi}}{\sigma})^2}$. To build this ADF we first define a set of bins spanning the whole range of ages, and having widths that increase with age (to account for the decreasing number of clusters at older ages). Then, for a cluster with age and uncertainty $t_A \pm \sigma$, we compute the probability that the age corresponds to a given bin, which is simply the difference of the error functions at the bin borders. By doing this for all clusters and age bins, we have the number-density of clusters in each age bin. By definition, the integral of the ADF over the whole range of ages is the number of clusters. Subsequently, bin widths can be adjusted to minimise the errors, so that the resulting ADF has statistically meaningful values over all ages.

3 OVERVIEW OF THE MASS-LOSS PROCESSES

Star clusters lose mass continually by a combination of processes associated with stellar evolution and dynamical interactions (both internal and external to the cluster). Robust analytical descriptions of the mass-loss processes - for clusters characterised by a wide variety of parameters and orbiting in different environments - have become available in recent years, with model parameters derived from theoretical grounds (e.g. Spitzer 1987; Lamers, Baumgardt & Gieles 2010) and N-body simulations (e.g. Baumgardt & Makino 2003; Gieles & Baumgardt 2008). Formally, the time-rate of change of mass of a cluster that was formed with the mass $M_i = M(0)$ can be expressed as:

$$\frac{dM}{dt} = \sum_{p=1}^6 \left(\frac{dM}{dt} \right)_p, \quad (1)$$

where the mass-loss process p are: (1) stellar evolution, (2) tidal effects by a steady field, (3) shocks with spiral arms, (4) encounters with GMCs, (5) evaporation, and (6) ejection. For processes (1) - (4) we adopt the semi-analytical approach of Lamers & Gieles (2006) and Lamers, Baumgardt & Gieles (2010). In what follows we assume that masses are always expressed in Solar masses (M_\odot)

¹ The Two Micron All Sky Survey, All Sky data release (Skrutskie et al. 2006)

² Galactic Legacy Infrared Mid-Plane Survey Extraordinaire (Benjamin et al. 2003)

³ www.univie.ac.at/webda

⁴ Catalog of Optically Visible Open Clusters and Candidates, Dias et al. (2002).

⁵ Upon request, the table with the age and distance from the Sun for the 442 nearby clusters is available from one of us (C.B.).

and time in Myr; also, we write the equations in terms of the remaining-mass fraction $\mu \equiv M/M_i$. For clarity, we provide below a brief description of these processes.

3.1 Stellar evolution

Since we are dealing essentially with disk clusters, we adopt the Solar-metallicity approximation given by Lamers & Gieles (2006), which is based on single-stellar population GALEV models (Anders & Fritze-v. Alvensleben 2003) and a Salpeter-like (Salpeter 1955) mass function:

$$\left(\frac{d\mu}{dt}\right)_{se} = -\mu \left(\frac{a}{t}\right) 10^{[(a-1)\log(qq) + qq^a + b]},$$

with $qq = \log(t) - 1.0$, $a = 0.255$, and $b = -1.805$. This process is relevant for $t > 10$ Myr.

3.2 Tidal effects

We adopt the semi-analytical description of the mass-loss of clusters on a steady-tidal field of Lamers, Baumgardt & Gieles (2010), which is expected to apply to a broad range of cluster conditions and orbit environments:

$$\left(\frac{d\mu}{dt}\right)_{tidal} = -\frac{\mu^{1-\gamma}}{t_o M_i^\gamma},$$

with $t_o = t_R \left(\frac{1-\epsilon}{\bar{m}^\gamma}\right) \left(\frac{R_G}{8.5 \text{ kpc}}\right) \left(\frac{v_G}{220 \text{ km s}^{-1}}\right)^{-1}$, $t_R = 13.3$ Myr for clusters with an initial concentration factor of the density King profile $W_0 = 5$, and $t_R = 3.5$ Myr for $W_0 = 7$; $\gamma = 0.65$ for $W_0 = 5$ and $\gamma = 0.8$ for $W_0 = 7$, thus, both γ and t_R are not independent parameters, since they can be expressed as a function of W_0 ; ϵ is the cluster orbit eccentricity; the average stellar mass at time t is given by the interpolation formula $\bar{m}(t) = 0.6193 - 0.0362\tau - 0.01481\tau^2 + 0.0022\tau^3$, where $\tau = \log(t)$; R_G is the cluster's Galactocentric distance, and v_G is the (assumed constant) rotation velocity. In what follows we take $v_G = 200 \text{ km s}^{-1}$ for orbits around the Solar neighbourhood.

3.3 Shocks with spiral arms

The energy gain and the mass loss due to the disruptive effect of spiral-arm passages of star clusters with planar and circular orbits around the centres of galaxies has been thoroughly studied by Gieles, Athanassoula & Portegies Zwart (2007). In particular, for the Solar neighbourhood, Gieles, Athanassoula & Portegies Zwart (2007) and Lamers & Gieles (2006) find:

$$\left(\frac{d\mu}{dt}\right)_{sp} = -5 \times 10^{-5} \frac{\mu^{0.3}}{(M_i/10^4 M_\odot)^{0.7}}.$$

3.4 Encounters with giant molecular clouds

Similarly to the spiral arms, Lamers & Gieles (2006) estimate the energy gain and mass loss due to encounters be-

tween clusters and GMCs. Assuming GMC parameters typical of the Solar neighbourhood, they find:

$$\left(\frac{d\mu}{dt}\right)_{GMC} = -5 \times 10^{-4} \frac{\mu^{0.3}}{(M_i/10^4 M_\odot)^{0.7}}.$$

The mass loss due to GMCs is thus 10 times higher than that of the spiral arms.

3.5 Ejection and evaporation

Stars can also escape from a cluster by means of ejection and evaporation. Ejection occurs when, after a single, close encounter with another star, a member ends up with excess velocity with respect to the escape velocity. Evaporation, on the other hand, is related to a series of more distant encounters that gradually increase a star's energy, eventually leading it to escape from the cluster. With the respective time scales taken from Khalisi, Amaro-Seoane & Spurzem (2007, and references therein), the mass loss associated with both processes are, respectively:

$$\left(\frac{d\mu}{dt}\right)_{ej} = -\frac{\bar{m}(G\mu)^{1/2}}{46(M_i R_{hm}^3)^{1/2}},$$

and

$$\left(\frac{d\mu}{dt}\right)_{ev} = -\frac{\bar{m}(G\mu)^{1/2} \ln(\gamma_c N)}{13.8(M_i R_{hm}^3)^{1/2}},$$

where the half-mass radius is given by $R_{hm} = 3.75 (M/10^4)^{0.1}$ (Larsen 2004), $\gamma_c = 0.11$ is the Coulomb factor, $N = M(t)/\bar{m}(t)$ is the number of stars at time t , and G is the gravitational constant.

3.6 The adopted procedure

In summary, given a cluster of initial mass M_i , and a set of model parameters (R_{GC} , W_0 , γ , ϵ , t_R), Eq. 1 should be solved to find the mass still bound to the cluster at a later time t , $M = M(t)$.

4 INTERPRETING THE LOCAL ADF

The Solar neighbourhood ADF has been subject to previous investigation. In particular, Lamers et al. (2005) and Lamers & Gieles (2006) employed the cluster dissolution processes 1–4 (Sect. 3) to study the ADF of 114 OCs closer than $d_\odot = 0.6 \text{ kpc}$ taken from Kharchenko et al. (2005). Their ADF can be reasonably well described by a nearly-constant SFR (in bound clusters of mass $10^2 < M(M_\odot) < 3 \times 10^4$) of $SFR = 400 M_\odot \text{ Myr}^{-1}$, corresponding to a surface formation rate $\Sigma_{SFR} \approx 350 M_\odot \text{ Myr}^{-1} \text{ kpc}^{-2}$, which is considerably lower than the $\Sigma_{SFR} = 700 - 1000 M_\odot \text{ Myr}^{-1} \text{ kpc}^{-2}$ inferred from ECs (Lada & Lada 2003), and the $\Sigma_{SFR} = 3000 - 7000 M_\odot \text{ Myr}^{-1} \text{ kpc}^{-2}$ from field stars (Miller & Scalo 1979). They also find evidence of a local burst of star formation that took place between 250–600 Myr ago (also present in Piskunov et al. 2006).

Besides cluster dissolution, observational completeness is also important for the ADF shape. High absorption and crowding, usually associated with fields dominated by disc

and bulge stars, affect cluster detectability, especially the faint and/or poorly-populated ones. Bonatto et al. (2006) show that most of the intrinsically faint and/or distant clusters must be undetected in the field, particularly in bulge/disc directions. They also find that the completeness-safe zone might extend up to $d_\odot \approx 1.4$ kpc inside the Solar circle, but considerably more outside.

Thus, to minimise observational completeness effects, we restrict the analysis to the region $d_\odot \leq 1$ kpc, which reduces the number of clusters to 442, but still a statistically significant sample. Besides, this condition also guarantees that we are dealing with clusters subject to somewhat similar physical conditions. By construction (Sect. 2), the resulting ADF (Fig. 1) is rather smooth, with small errors over all ages, except for $t_A \gtrsim 3$ Gyr, which reflects the scarcity of Gyr-old clusters in the region. Also conspicuous are the excesses between $200 \lesssim t_A(\text{Myr}) \lesssim 600$, and especially for $t_A \lesssim 10$ Myr (see below). Since we work with a significantly larger sample than Lamers et al. (2005) and Lamers & Gieles (2006), our approach provides a better definition of structures in the ADF.

4.1 ADF simulation

Instead of assuming particular values for the several model parameters (R_{GC} , W_0 , γ , t_R , ϵ , number, age, initial mass, and the orbit of clusters), we adopt a simplifying approach. Starting with a pre-defined SFR, we compute the time-evolution of the individual mass of star clusters created with parameters covering the observed range in orbits around the Solar circle (Lamers, Baumgardt & Gieles 2010). We assume that the relevant model parameters can take on any value within $0.0 \leq \epsilon \leq 0.8$ (also allowing for circular orbits), $5 \leq W_0 \leq 7$, $0.65 \leq \gamma \leq 0.8$, and $3.5 \leq t_R(\text{Myr}) \leq 13.3$ (the latter two are expressed as a function of W_0 as $t_R = 37.8 - 4.9W_0$ and $\gamma = 0.275 + 0.075W_0$); also, given the restriction $d_\odot \leq 1$ kpc, we have $7.5 \leq R_{GC}(\text{kpc}) \leq 9.5$. Each cluster is created (at time t_A) with an individual mass in the range $M_{\min} < M_i(M_\odot) < M_{\max}$, but following the number-frequency (or probability) $dN/dM_i \propto M_i^{-2}$ (e.g. Elmegreen 2008)⁶. We adopt $M_{\min} = 10 M_\odot$ and $M_{\max} = 7.5 \times 10^4 M_\odot$ as the minimum and maximum initial cluster mass, respectively. Then we solve Eq. 1 to find the mass remaining in each cluster after evolving for a time from $t = 0$ to $t = t_A$, and build the simulated ADF. Similarly to Lamers & Gieles (2006), we assume $100 M_\odot$ as the minimum cluster mass for completeness not being an issue to detectability, i.e. only clusters more massive than $100 M_\odot$ are accounted for in the ADF. According to this approach, the number of free parameters reduces essentially to the SFR shape.

The following steps are taken: (i) We assume that all star formation occurs in clusters, define the SFR and compute the total mass ($M_{\text{tot}} = \int SFR(t) dt$) converted into stars over the Galaxy age; in the case of a non-constant SFR, this should be done separately for each SFR segment (or period of time). (ii) We assign the initial mass M_i (see above) for one cluster. (iii) Next, we randomly assign the cluster age t_A (it should be within the corresponding SFR

time segment), and the model parameters. (iv) Steps (ii) and (iii) are repeated for more clusters, until the sum of initial masses equals M_{tot} . (v) Then we solve Eq. 1 for all clusters from $t = 0$ to t_A , and keep only those with $M(t_A) > 100 M_\odot$. (vi) Finally, stochastic effects are minimised by repeating steps (ii) to (v) several times (N_{sim}). In the present case we use $N_{\text{sim}} = 100$, and solve Eq. 1 for $M = M(t)$ by means of a 4th order Runge-Kutta method, with a fixed time step of 1 Myr.

4.2 Constraining the local SFR

Given the conspicuous excesses (Fig. 1), it is clear that the Solar neighbourhood cluster ADF cannot result from a constant SFR. Instead, the best match has been obtained with the segmented SFR: $SFR = 5040 M_\odot \text{Myr}^{-1}$ ($\Sigma_{SFR} \approx 1600 M_\odot \text{Myr}^{-1} \text{kpc}^{-2}$) for $t_A \leq 9$ Myr, $SFR = 4800 M_\odot \text{Myr}^{-1}$ ($\Sigma_{SFR} \approx 1500 M_\odot \text{Myr}^{-1} \text{kpc}^{-2}$) for $220 \leq t_A(\text{Myr}) \leq 600$, and $SFR = 2400 M_\odot \text{Myr}^{-1}$ ($\Sigma_{SFR} \approx 760 M_\odot \text{Myr}^{-1} \text{kpc}^{-2}$) elsewhere (bottom panel of Fig. 1). Integrating the segmented-SFR ADF over time yields the same number of clusters as that of the observed ADF. Also, the 1σ boundaries of the adopted solution (shaded region in Fig. 1), obtained after 100 different simulations, are very narrow over most of the cluster ages. To check how constrained is this solution, we apply the same procedure to SFRs that are 20% higher and lower than the adopted SFR over all time periods. Overall, both SFRs provide a much poorer description of the observed ADF than the segmented SFR, especially for clusters younger than ~ 300 Myr. Thus, we adopt 20% as the SFR uncertainty. As expected, the ADF produced by a constant SFR ($2500 M_\odot \text{Myr}^{-1}$) fails to describe the observed excesses.

Considering the above arguments, the average values (over the full age range) of the SFR and surface SFR are $\overline{SFR} \approx (2500 \pm 500) M_\odot \text{Myr}^{-1}$ and $\overline{\Sigma_{SFR}} \approx (790 \pm 160) M_\odot \text{Myr}^{-1} \text{kpc}^{-2}$. Given the higher number of clusters in our sample, we find a Σ_{SFR} more than twice that of Lamers et al. (2005) and Lamers & Gieles (2006), considerably more consistent with that inferred from ECs by Lada & Lada (2003), but still significantly lower ($\sim 16\%$) than the rate implied by field stars (Miller & Scalo 1979). We also compute the fraction of clusters that do not survive the first 10 Myr, $91.2 \pm 2.7\%$, which agrees with the rate of cluster dissolution after the embedded phase (e.g. Lada & Lada 2003).

On average, $\sim 3.3 \times 10^5$ clusters are created (at $d_\odot < 1$ kpc) in each simulation with the segmented SFR. This implies that less than 0.15% of the clusters ever formed in the Solar neighbourhood can be observed (i.e. having mass $\gtrsim 100 M_\odot$). And, if the same SFR applies to $R_{GC} = 7.5 - 9.5$ kpc, $\sim 10^7$ clusters have been created in this region since Galaxy formation.

5 SUMMARY AND CONCLUSIONS

In this paper we analyse properties of the Solar neighbourhood SFR, by means of a statistically significant ADF built with 442 star (embedded and open) clusters closer than 1 kpc from the Sun. By adopting a simplifying approach, in which the mass evolution of artificial clusters is followed

⁶ This is done by $M_i = \frac{M_{\min}}{1-n(1-M_{\min}/M_{\max})}$, where n is uniformly distributed within $[0,1]$.

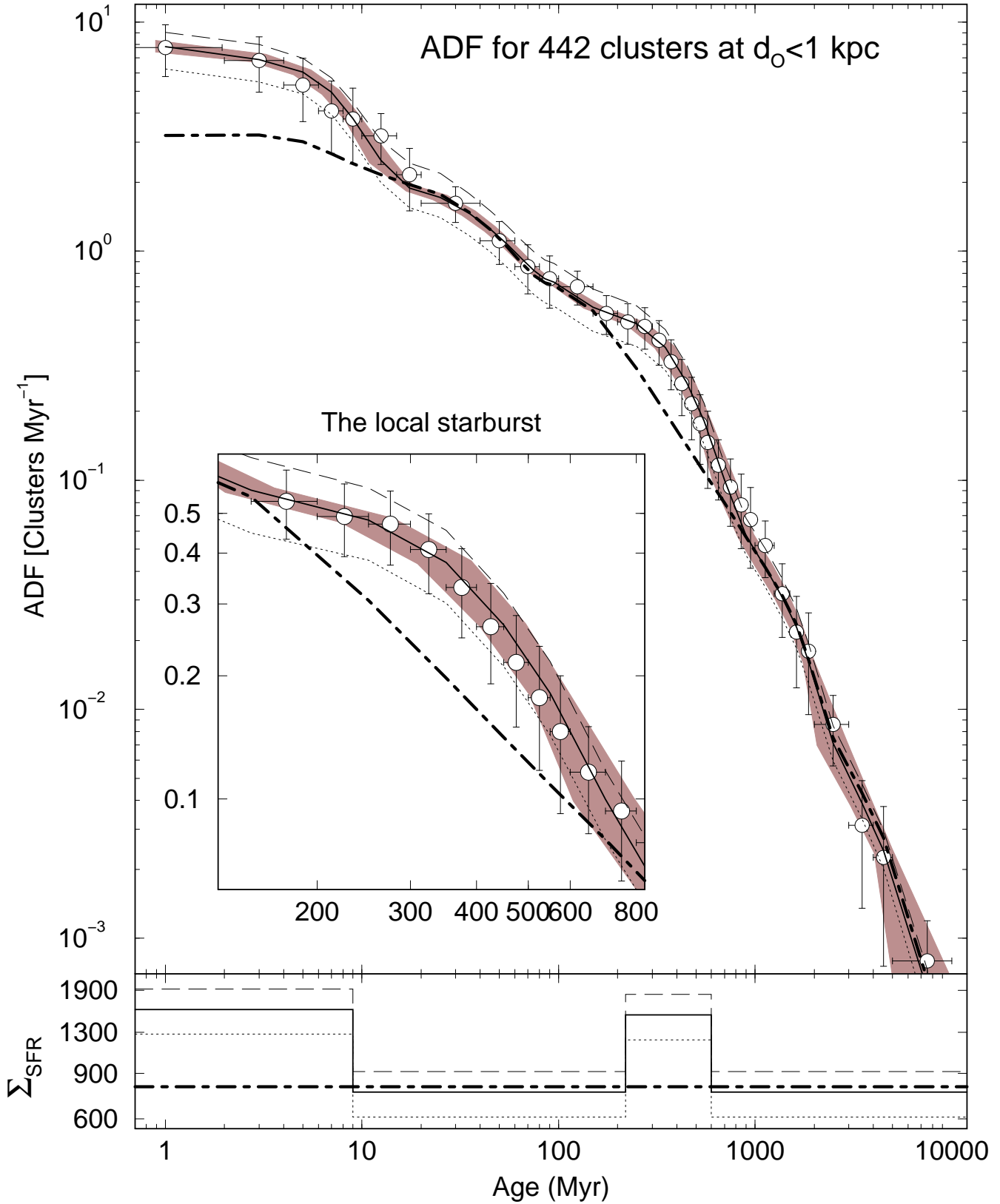


Figure 1. Top: The Solar neighbourhood ADF (circles) is well reproduced by a segmented SFR (heavy-solid line) with enhanced rates at ≤ 9 Myr and 220 – 600 Myr and small Stochastic fluctuations over 100 simulations (shaded region). Also shown are the ADFs produced by Σ_{SFR} 's 20% higher (dashed line) and lower (dotted) than above, together with a constant Σ_{SFR} (heavy dot-dashed line). Inset: Blow-up of the local starburst period. Bottom: The Σ_{SFR} 's (in $M_\odot \text{ Myr}^{-1} \text{ kpc}^{-2}$) used in the top panel.

over time, we reduce the problem to essentially finding the SFR.

The artificial clusters embody parameters and conditions expected to apply to most actual star clusters orbiting not far from the Solar circle. To simulate the observed ADF, we employ semi-analytical descriptions of the mass-loss process responsible for cluster dissolution, and assume that only clusters with a present-day mass above $100 M_{\odot}$ can be effectively observed (i.e., take part in the ADF).

The best match between observed and simulated ADFs corresponds to a non-constant SFR, with enhanced rates for ages the ≤ 9 Myr and $220 - 600$ Myr (the so-called local starburst). The average rate is $\overline{SFR} \approx (2500 \pm 500) M_{\odot} \text{ Myr}^{-1}$, corresponding to the average density $\overline{\Sigma}_{SFR} \approx (790 \pm 160) M_{\odot} \text{ Myr}^{-1} \text{ kpc}^{-2}$. These values agree with the formation rate inferred from ECs, but represent only $\sim 16\%$ of the rate implied by field stars. Both the local starburst and the recent formation (≤ 9 Myr) have ADF amplitudes suggesting periods with a SFR about twice the average value. We also find that $91.2 \pm 2.7\%$ of the clusters created in the Solar neighbourhood dissolve before 10 Myr, which is consistent with the rate of EC dissolution.

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